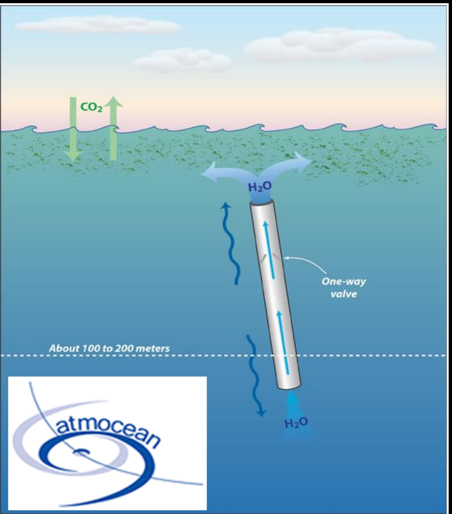
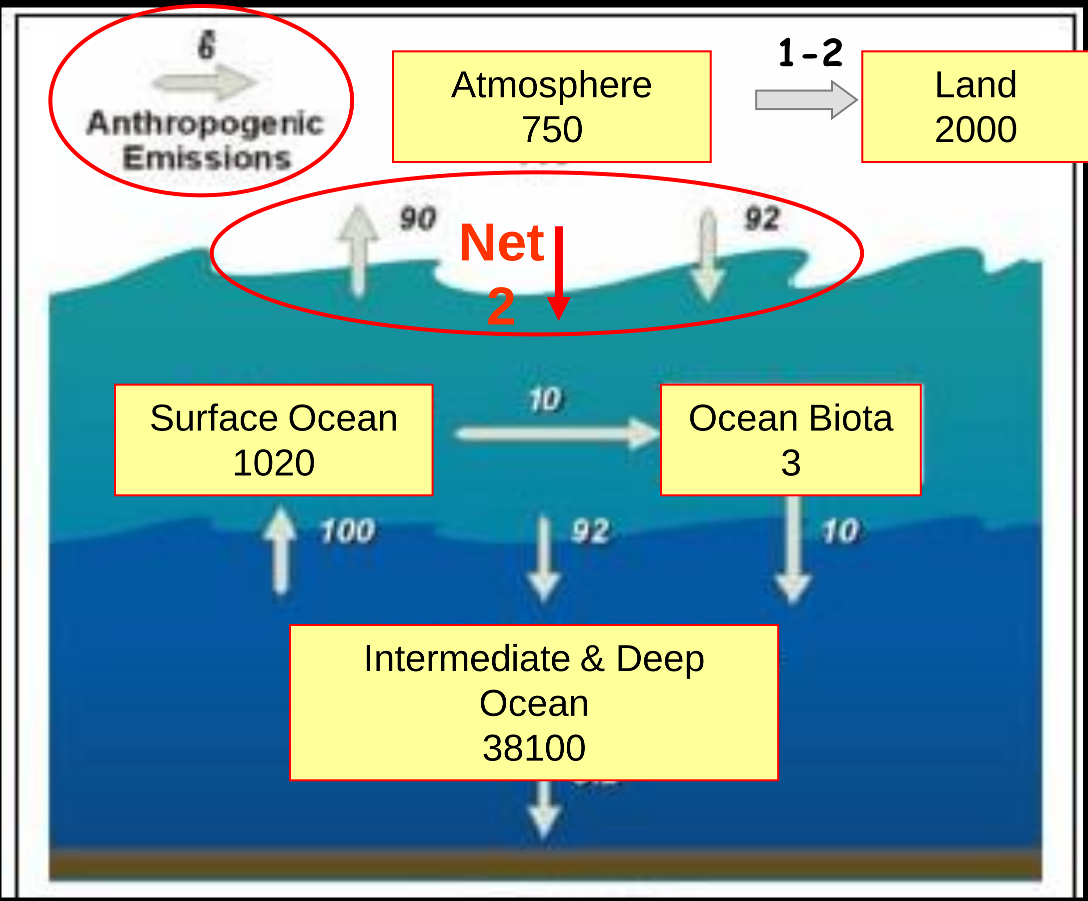
Geoenginnering – Ocean Schemes
Cliff Law



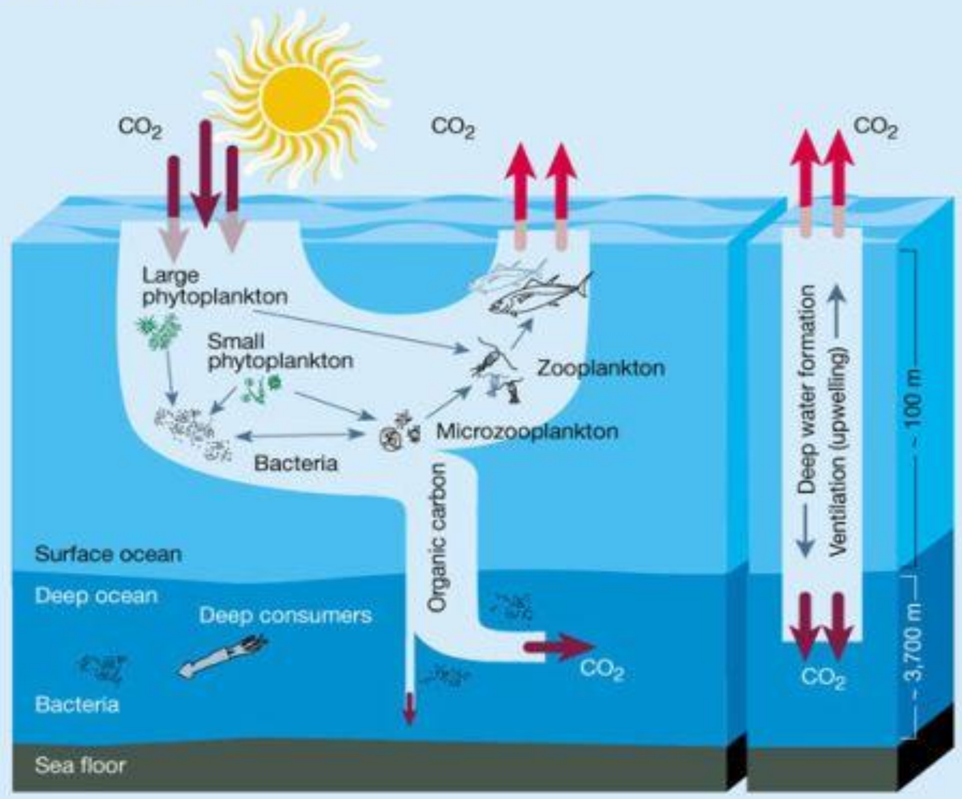
The Ocean Carbon sink

Gt (billion tonnes)



- Removes a third of current CO_2 emissions & has taken up 500 of 1300 Gt total anthropogenic emissions
- Has huge carbon storage capacity compared to other compartments
- Deep ocean mixes very slowly so slow return to atmosphere

Ocean carbon uptake - the Biological & Solubility Pumps



A small proportion of organic carbon falls to the sea floor, where it may get buried under sediments and lithify.

from:Nature 407, 12th October 2000

Ocean CDR Options

- **Direct addition**
Sub-seabed CO_2 storage
Liquid CO_2 storage
biomass storage in deep ocean

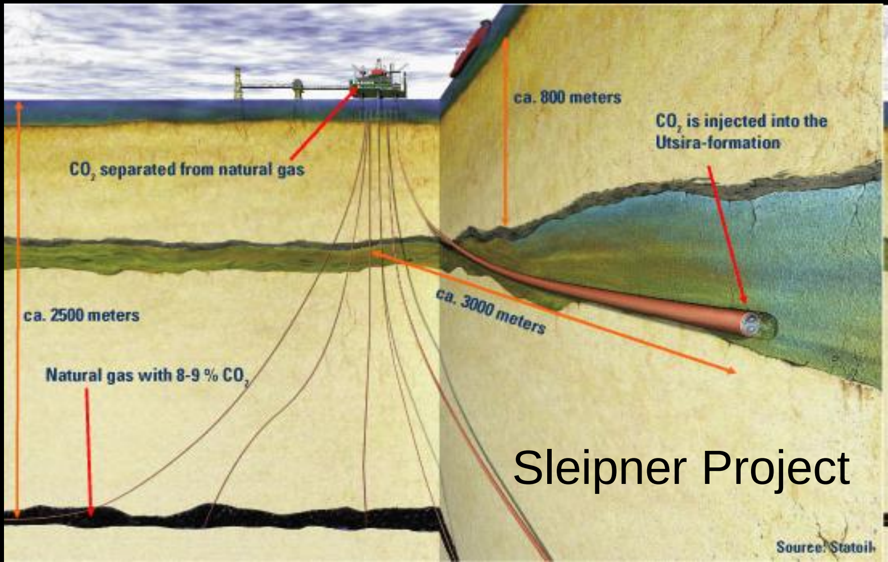
- **Chemical enhancement**
Liming the ocean
enhancing weathering

- **Physical enhancement**
increasing CO_2 in down-welling

- **Biological enhancement**
Artificial upwelling
Fertilisation

Direct addition – sub-seabed CO_2 storage

- CO_2 separated from flue gases, compressed and transported by pipeline or vessel to the selected geological storage site using established technology.
- Large storage potential in sub-sea saline aquifers & depleted oil and gas fields (with existing infrastructure) - could store more than 50% of global CO_2 emissions for the next 50 years.
- Storage sites require low probability of CO_2 leakage; highly impermeable cap rocks; geological stability; absence of leakage paths
- Trials - storage in several regions worldwide including Sleipner Project, North Sea



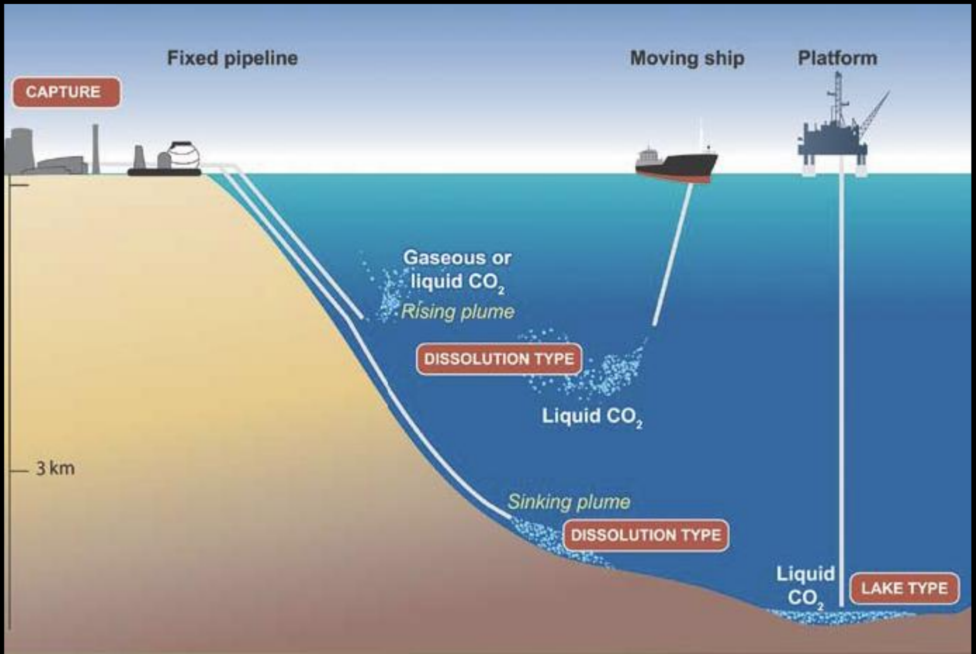
Sleipner Project

Direct addition - Seafloor Storage

At >3000m, liquid CO_2 is denser than surrounding sea water, and accumulates as a pool of liquid CO_2 and hydrate.

CO_2 lakes would dissolve slowly - return to atmosphere dependent on dynamics and depth. Models suggest deep ocean CO_2 isolated for several centuries with 0-85% retained in the ocean over 500 years at depths of 1000-3000 m (IPCC)

Injection from a moving ship towing a pipe to produce a seawater plume of lower initial CO_2 concentrations, with potentially less impact than seafloor storage but over larger area.



Direct addition - Seafloor Storage

Risks

Measurable changes in ocean chemistry
Organisms near injection may be harmed.
Effect on deep-ocean ecosystems not known.
Will enhance ocean acidification

Trials

Proposed field experiment to inject off Hawaii coast & coast of Norway, both halted in response to protests by Environmental groups

Liquid carbon dioxide deep under water (just over 3600 M)
Source: Monterey Bay Aquarium Research Institute

Direct addition - Biomass deposition

Crop residue deposited where river deltas fall off the edge of the continental shelf into deep water. (Mississippi/Gulf of Mexico, Nile/Mediterranean Sea)

Buried in silt on the sea floor sequesters carbon for long time assuming that it is degraded slowly

Risks

Low; localised deoxygenation but
Where will the biomass be grown?
& what about competition with crops & biofuels?

Alternative growing large macrophyte (kelp) rafts and sinking to deep ocean

Chemical enhancement of ocean alkalinity

Sea water acidity resulting from CO_2 addition is naturally neutralized by alkalinity from the slow dissolution of carbonate minerals from sea-floor sediments and weathering on land.

Artificially increase ocean alkalinity

• Add carbonate to the ocean or

• React CO_2-rich exhaust gases from industry with seawater to produce carbonic acid solution, which is then reacted with crushed carbonate to form bicarbonate:-

$CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2\ HCO_3^-$

Resulting solution released to ocean where bicarbonate will not react directly with or release CO_2 into atmosphere

Models suggest this may be three times more effective at slowing atmospheric CO_2 release than deep sea storage over 1000 yrs (Caldeira & Rau, 2000)

Chemical enhancement of ocean alkalinity

1.5 mole of carbonate mineral must be dissolved for each mole of anthropogenic CO_2 permanently stored in the ocean

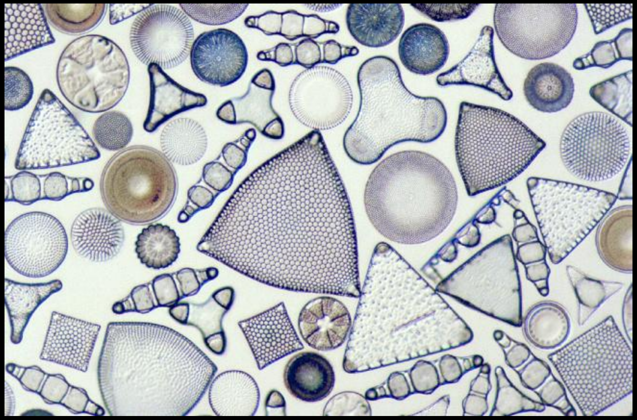
Sedimentary carbonates are abundant (5 x 10^{17} tonnes), ~10,000 times greater than the mass of fossil-fuel carbon.

Worldwide, 3 Gt $CaCO_3$ is mined annually; large-scale deployment of carbonate neutralization approaches requires greatly expanded mining and transport of limestone and attendant environmental impacts.

“Liming” the ocean converts CO_2 to a form that does not exchange with atmosphere & could reduce or reverse ocean acidification…

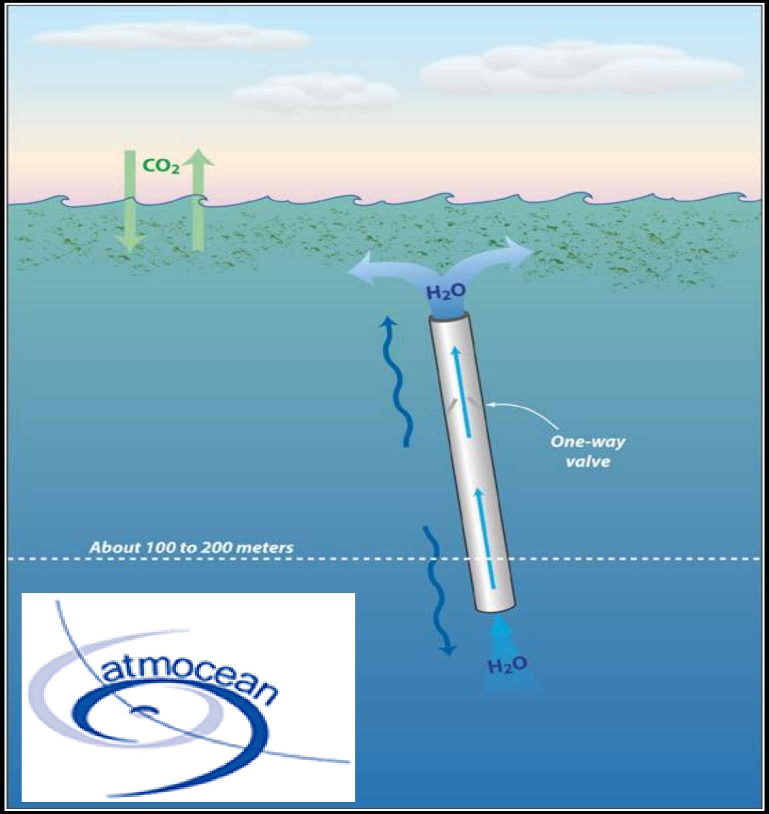
Biological enhancement via phytoplankton photosynthesis

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$



To fix carbon, phytoplankton need light & nutrients (nitrogen, phosphate, iron)

Artificial upwelling

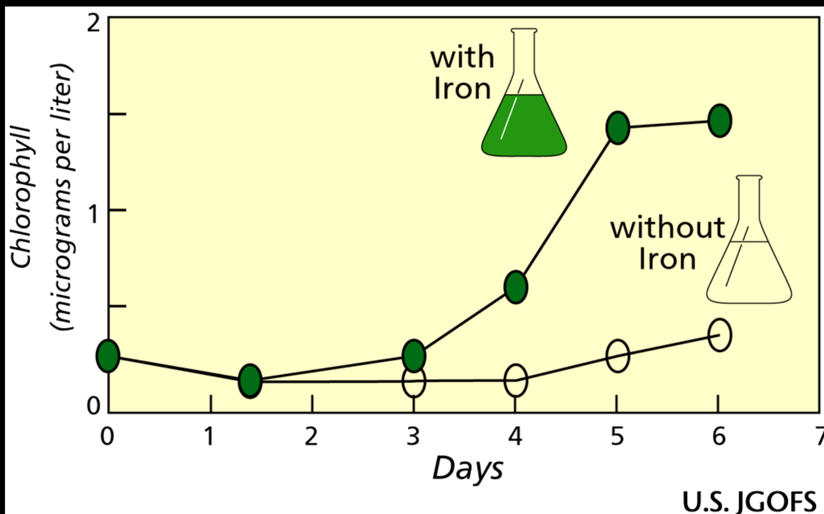


Trial deployments demonstrate technically challenging
Effectiveness questioned (supply CO_2 as well as nutrients to surface waters)

Biological enhancement - Nitrogen (urea) fertilisation

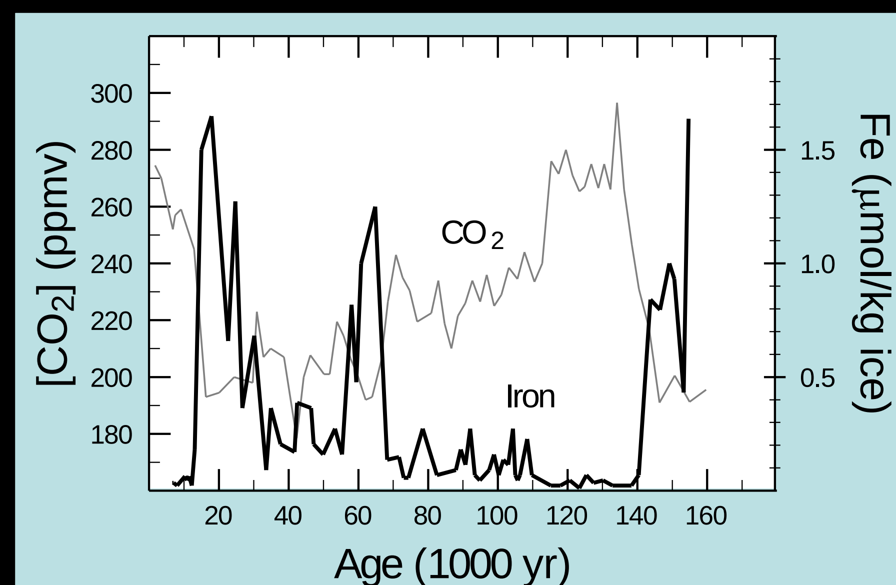
- Stimulate phytoplankton growth (and ocean C uptake) in low N waters
- small-scale trial in the Sulu Sea (Phillipennes) by ONC (Sydney, Australia)
- Risks to ecosystem such as toxic algal blooms raised by scientific community
- forthcoming trial in Chinese territorial waters (& Tasman Sea?)

Biological enhancement - iron fertilisation



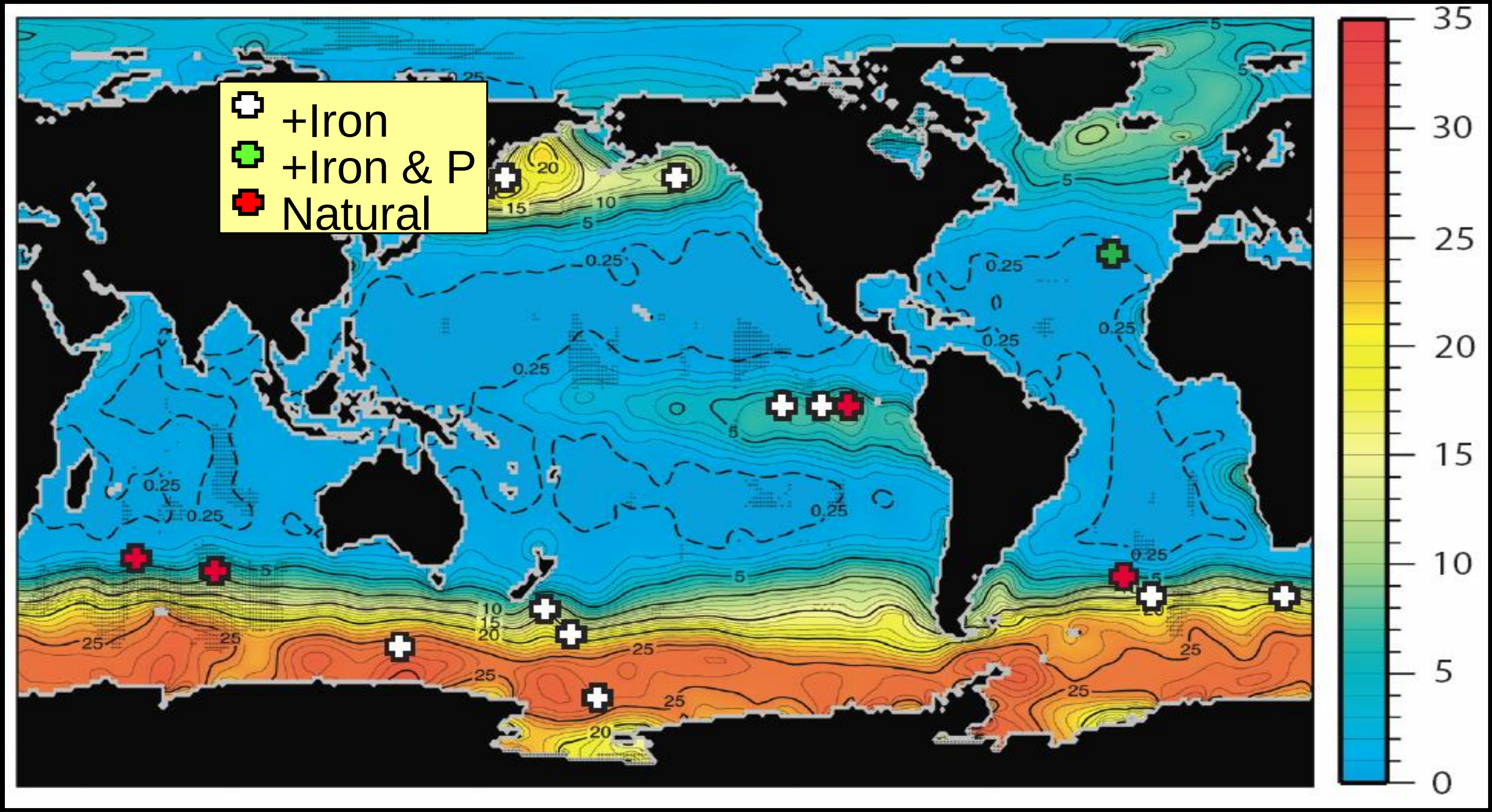
Evidence from bottle experiments in low iron water

Evidence from the palaeorecord that iron availability controls atmospheric CO_2



Biological enhancement - iron fertilisation

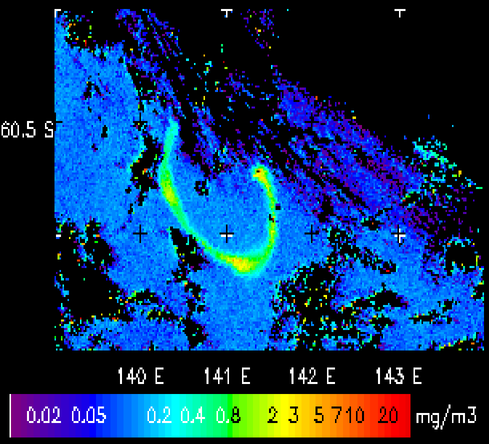
Evidence from *in situ* iron experiments in low iron waters

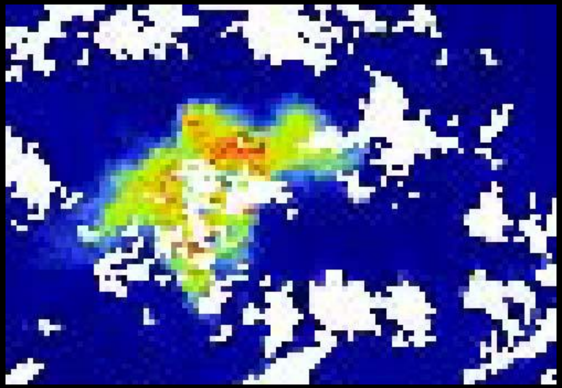


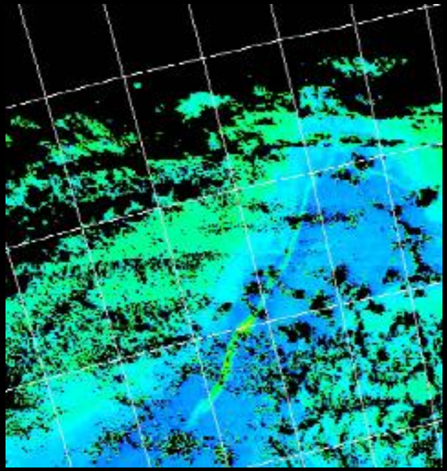
Nitrate (µmol/l)

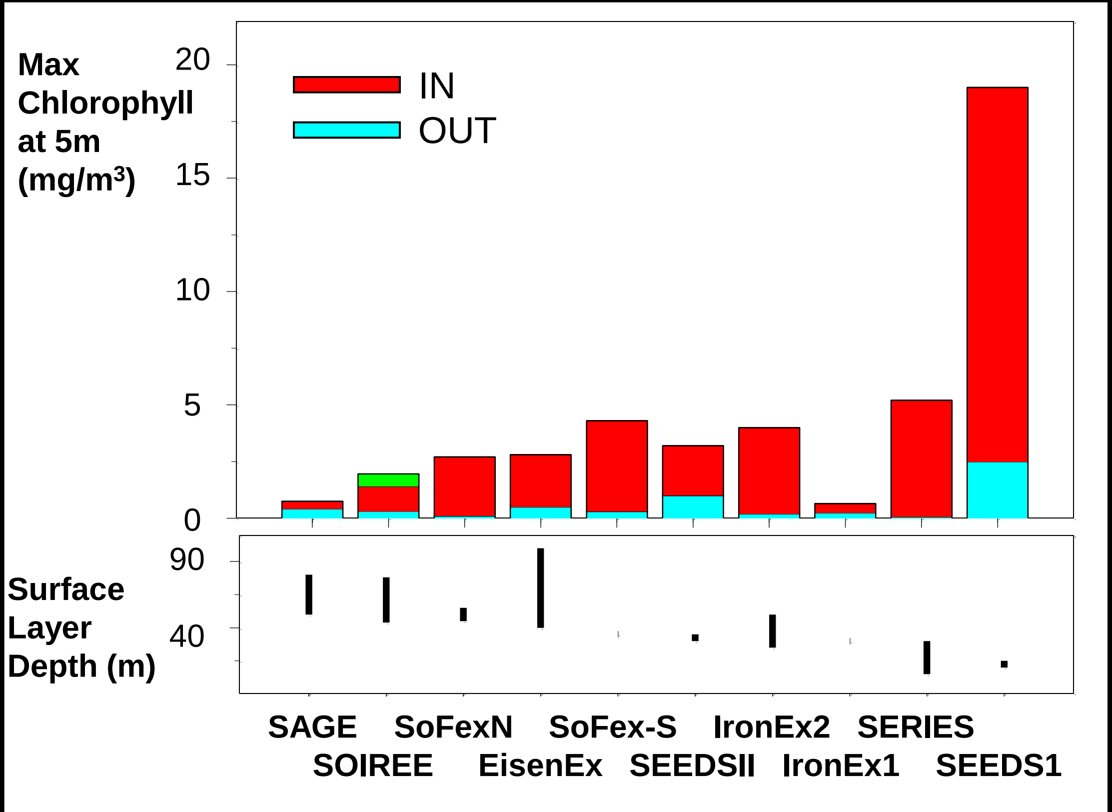
Boyd, Jickells, Law *et al* (2007)

Most iron addition experiments resulted in phytoplankton blooms



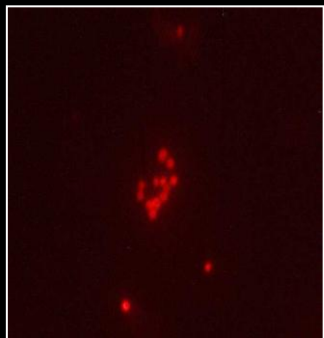


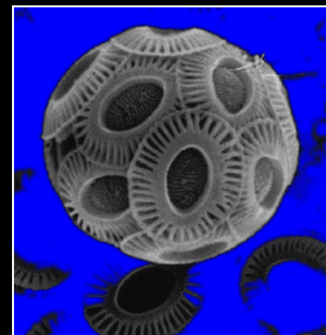




changes in phytoplankton community….

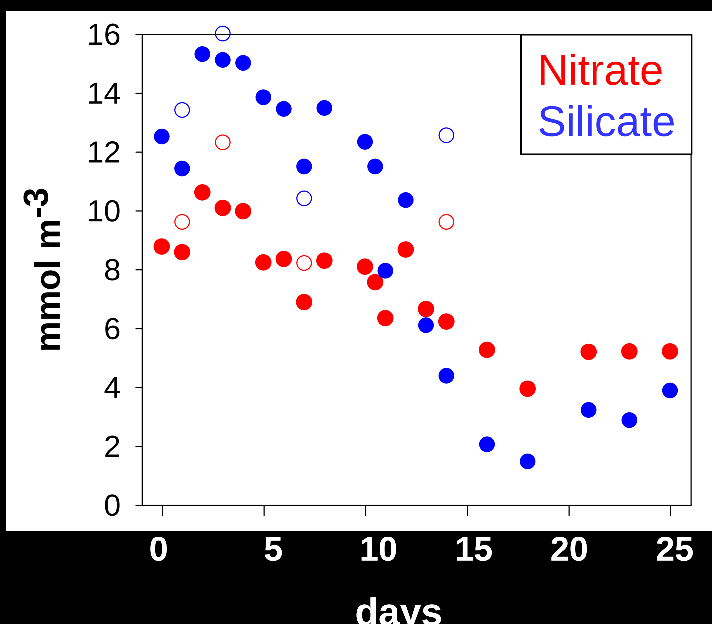
Size

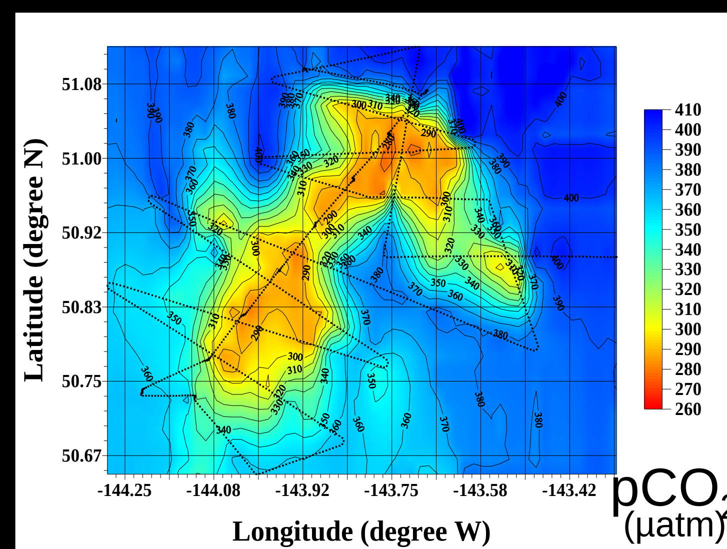




Nutrient drawdown

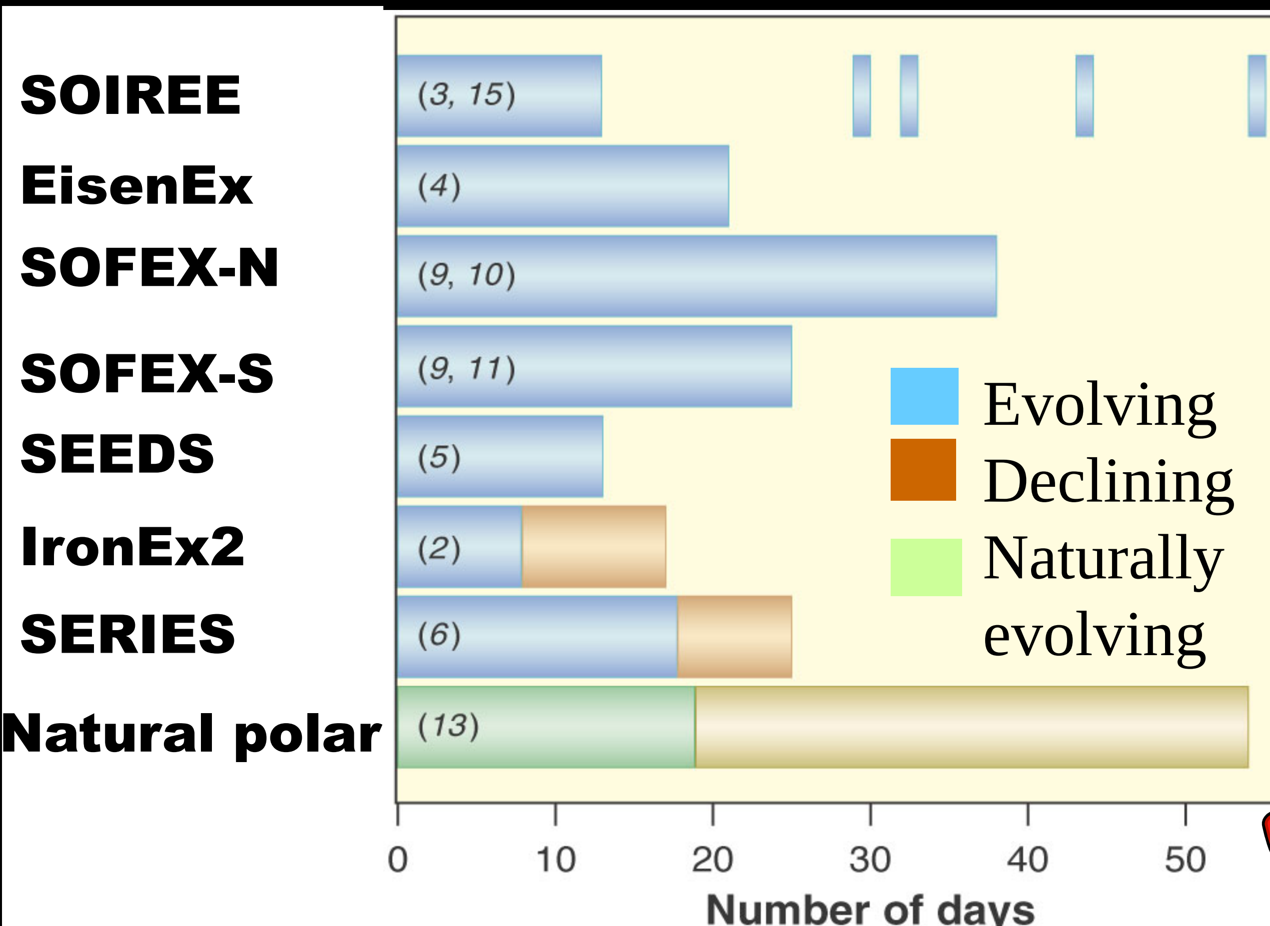
C fixation

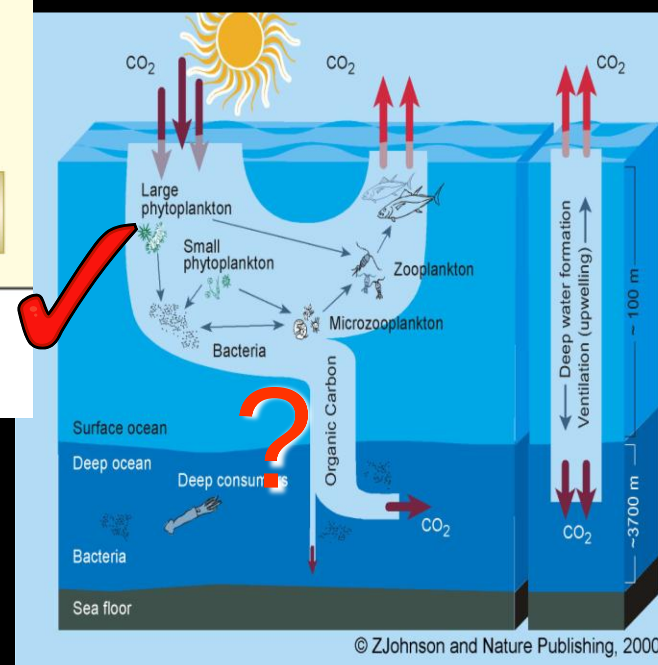




Boyd et al. 2004, Law et al, 2006

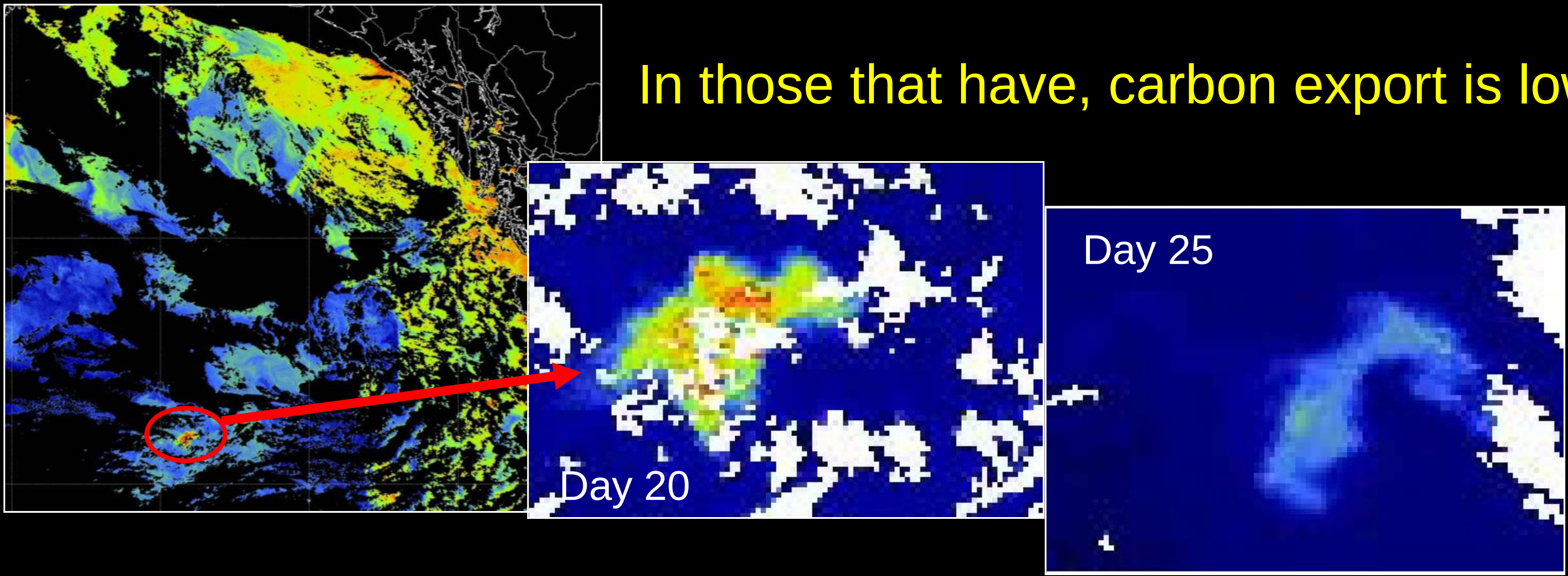
But few have captured the export of carbon to deep water

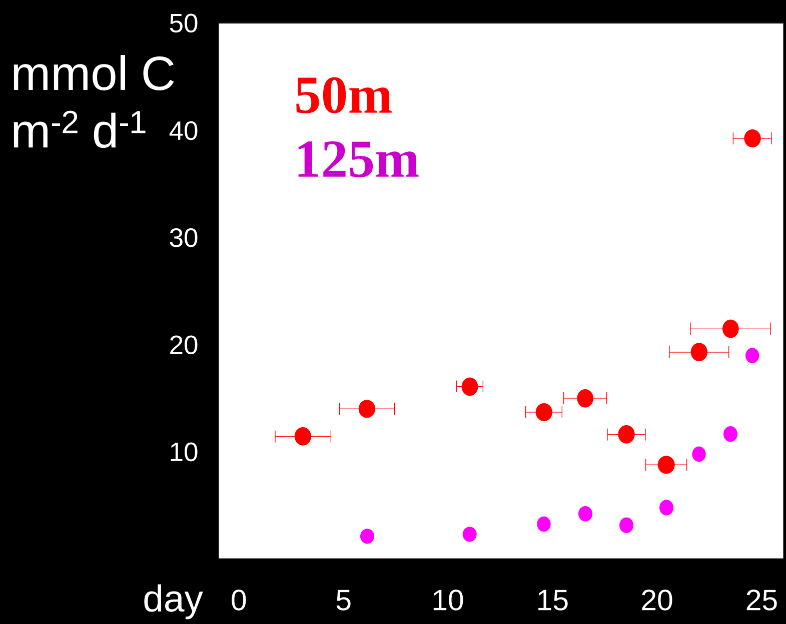




Boyd (2004)

In those that have, carbon export is low

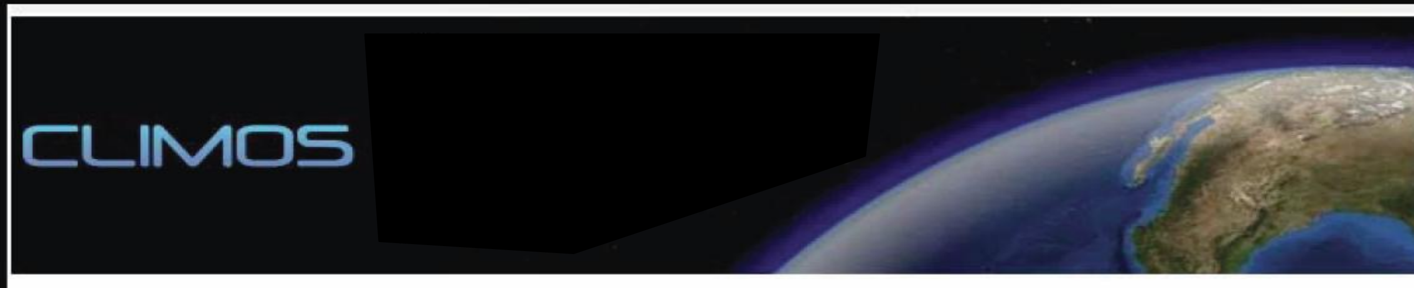




Particulate carbon flux

Transfer efficiency
18% to 50m
8% to 125m

Boyd, Law *et al*, 2004



"highest greenhouse gas mitigation of all available methods"

- Science advisory board
- Code of conduct
- Assessment/verification methodology
- Plans to conduct the first moderate-scale (40,000 square km) 'demonstration experiment' in the Southern Ocean

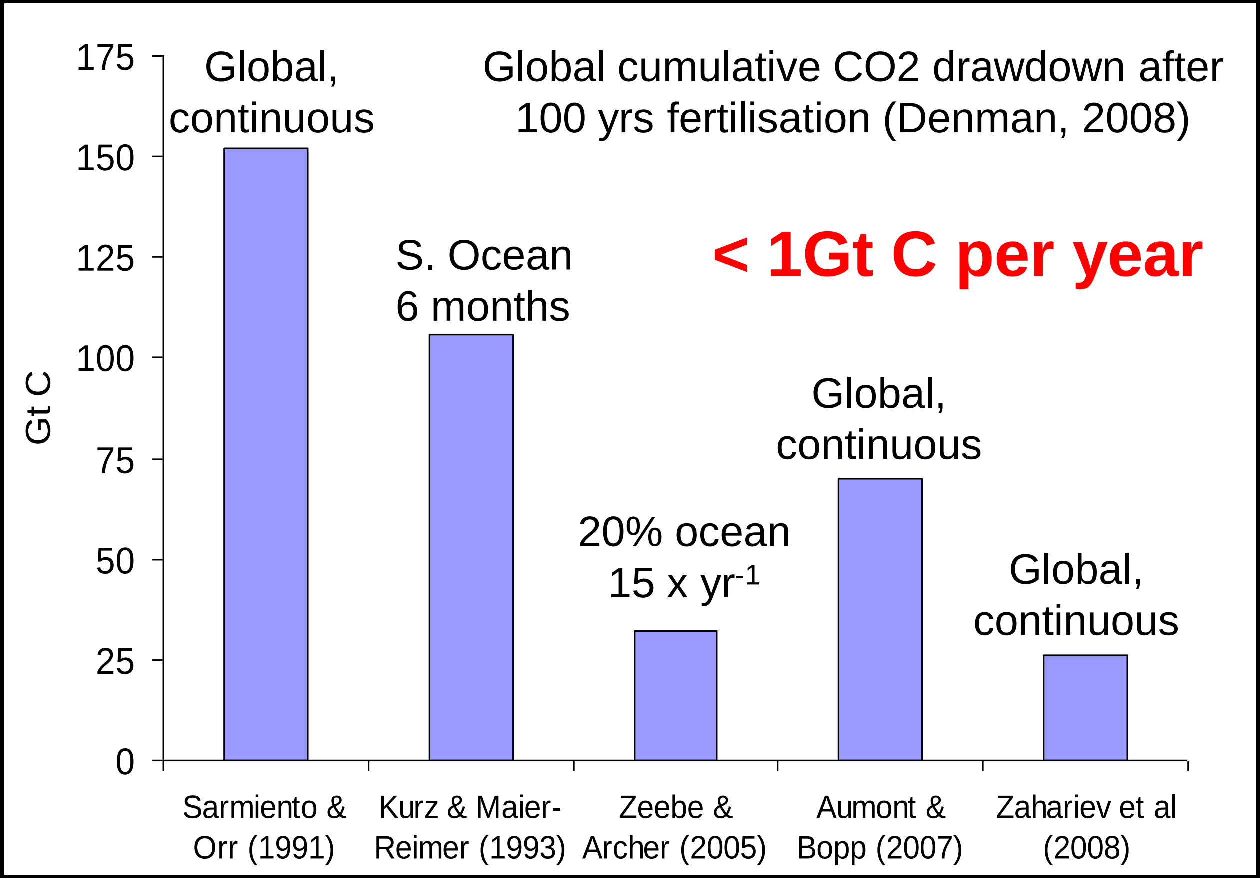
CLIMOS

BRIEFING ON
OCEAN IRON FERTILISATION
AS A CLIMATE CHANGE MITIGATION TECHNIQUE AND THE
POTENTIAL ROLE OF
NEW ZEALAND

Thursday, 17 July, 2008, 12:00-2:00 PM

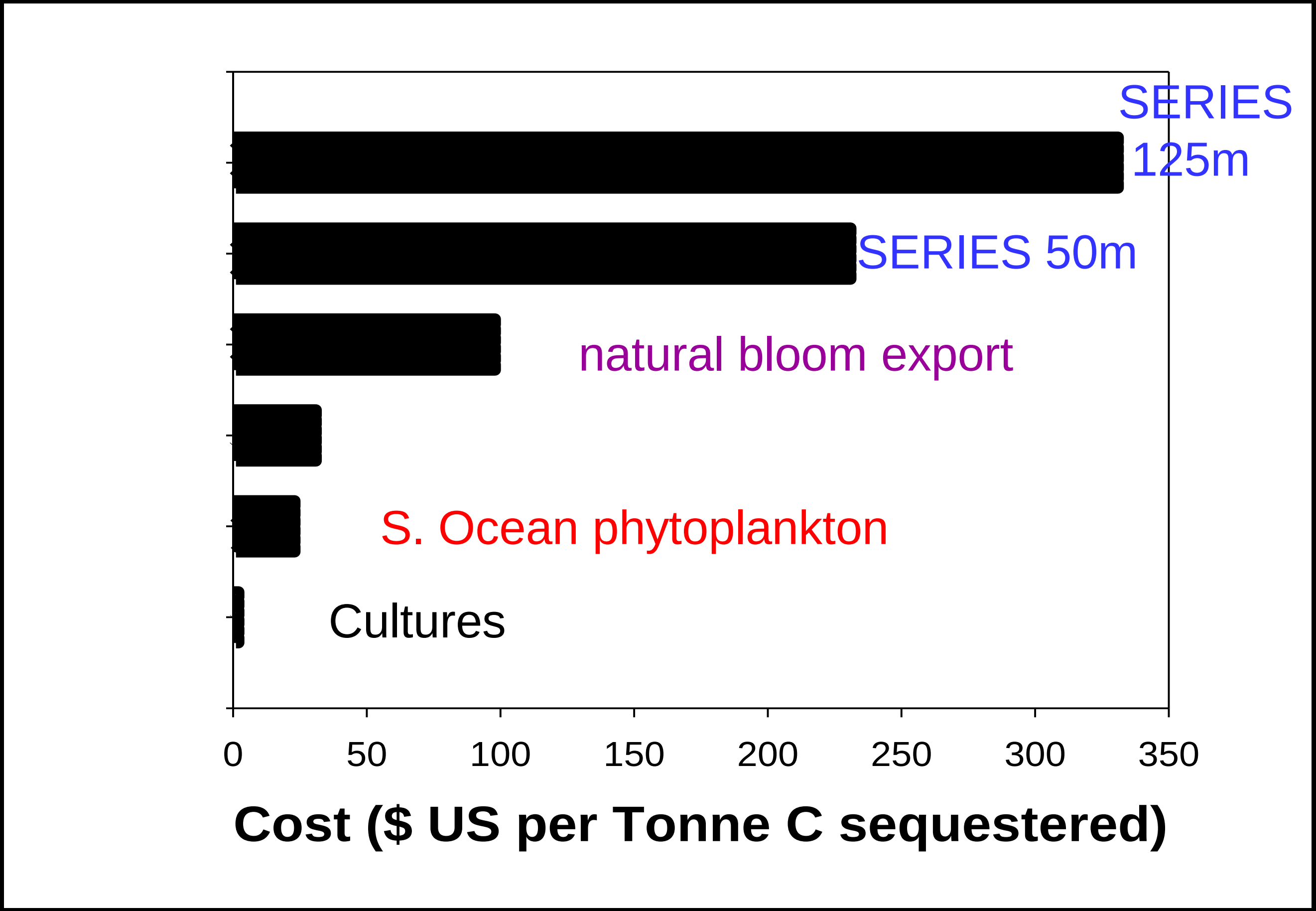
Effective CO_2 drawdown ?

- what do models show



Sustained fertilization (100 years) will achieve a decrease in atmospheric CO_2 of 33 µatm (compared to current 390 µatm) (Aumont & Bopp, 2007)

Cost-effective CO_2 drawdown?

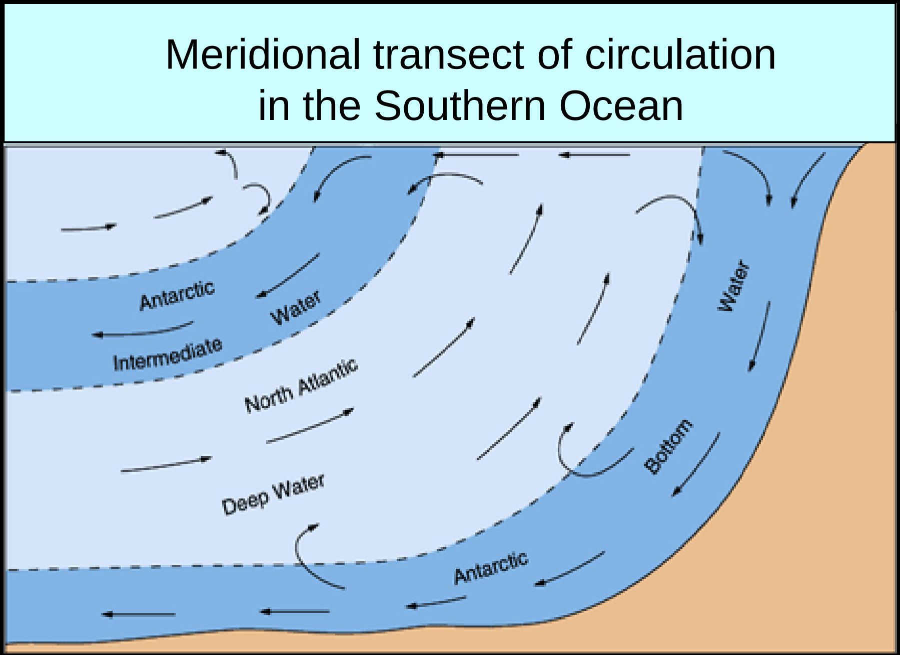


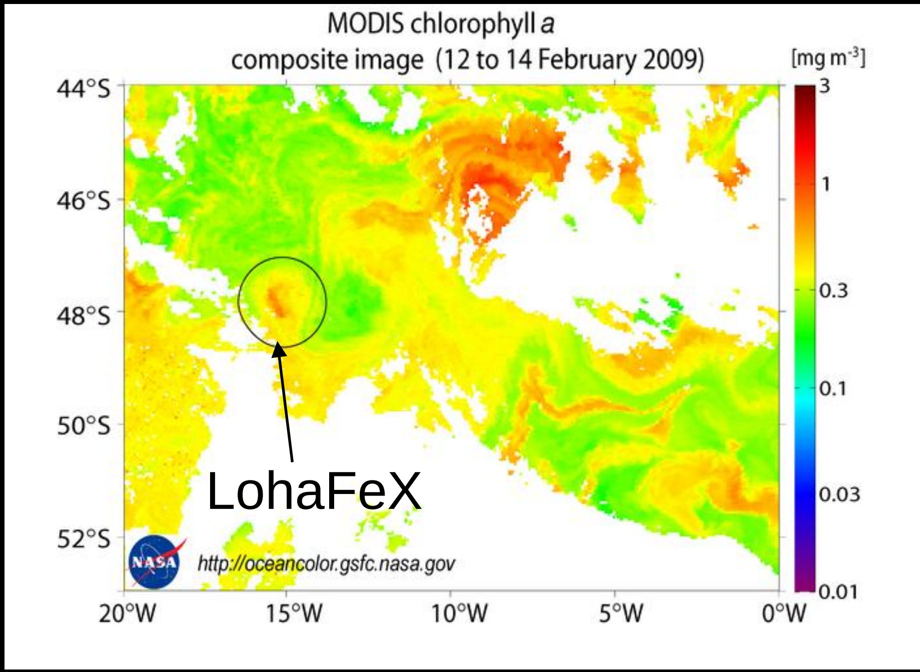
Field experiments suggest iron fertilisation is considerably more expensive than initial laboratory experiments suggested….

Boyd & Browman (*2009)*

Is the carbon sequestration verifiable & permanent?

- Attribution more difficult than in terrestrial systems due to circulation
- Retention below 100-yr horizon (500m) only in certain regions
- Difficult to distinguish carbon export from natural & iron-fertilised blooms

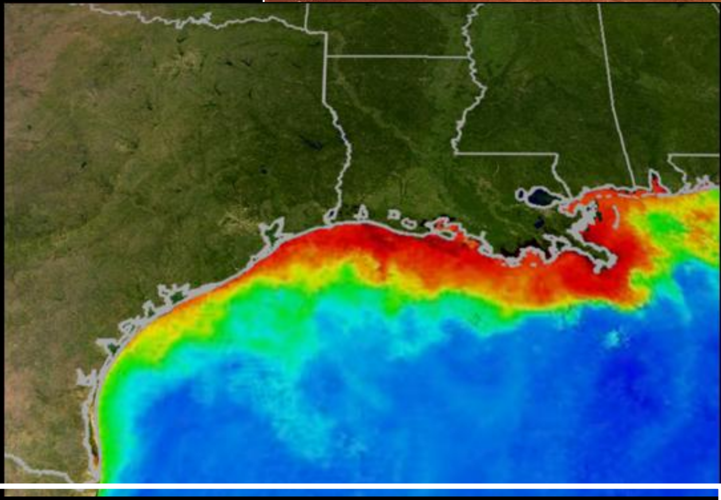




Are there unintended side-effects?

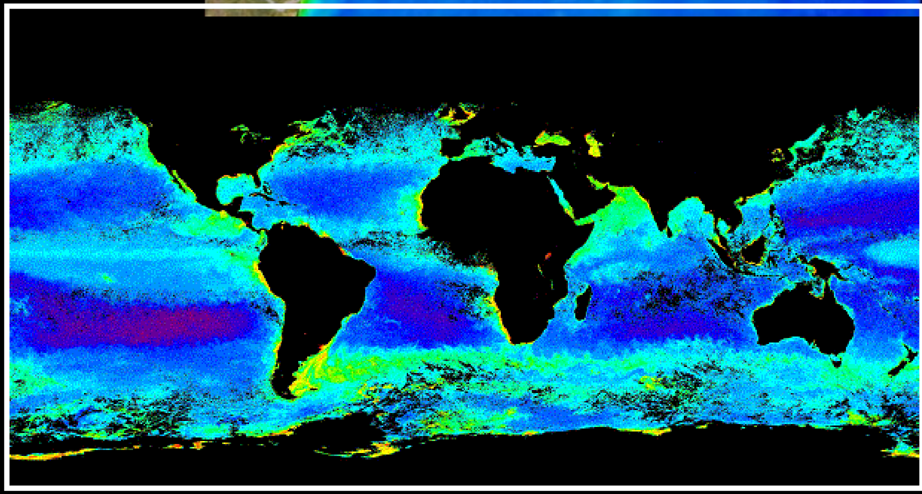
Biodiversity

- altered phytoplankton community, toxic algal blooms?



Nutrient “robbing” reduces productivity
In far-field regions

Models show expansion of
nutrient-deplete ocean gyres



Increased greenhouse gas production

- models predict increased ocean
nitrous oxide production

Are there unintended side-effects?

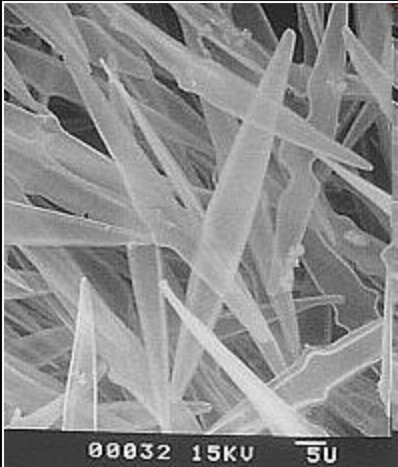
Toxic diatoms and domoic acid in natural and iron enriched waters of the oceanic Pacific

Mary W. Silver[a,1], Sibel Bargu[b], Susan L. Coale[a], Claudia R. Benitez-Nelson[c], Ana C. Garcia[b], Kathryn J. Roberts[a], Emily Sekula-Wood[c], Kenneth W. Bruland[a], and Kenneth H. Coale[d]

“ in phytoplankton samples from SOFeX and IronEx II, we found substantial amounts of DA associated with Pseudo-nitzschia. Indeed, at SOFeX in the Antarctic Pacific, DA reached 220 ng L^{-1}, levels at which animal mortalities have occurred on continental shelves……

…Given that iron fertilization……..has been proposed to enhance phytoplankton growth.….. consideration of the potentially serious ecosystem impacts associated with DA is prudent.”

Pseudo-nitzschia



Conclusions

- A number of marine geoengineering options; many theoretical & untested
- The most "tested" approach to date, iron fertilisation, has limited potential & potential side-effects
- Most techniques have been assessed at the cost & implementation level, with little consideration of direct & indirect impacts
- A generic assessment framework is required, that considers effectiveness, permanence, verification, side-effects, monitoring & attribution & reversibility
- Legislation (and policy) are critical in moving forward the debate & the science

1. SRM (Solar Radiation Management)

- Artificial aerosol production by spraying seawater or enhancing natural aerosol production by fertilisation (covered by Mike Harvey)

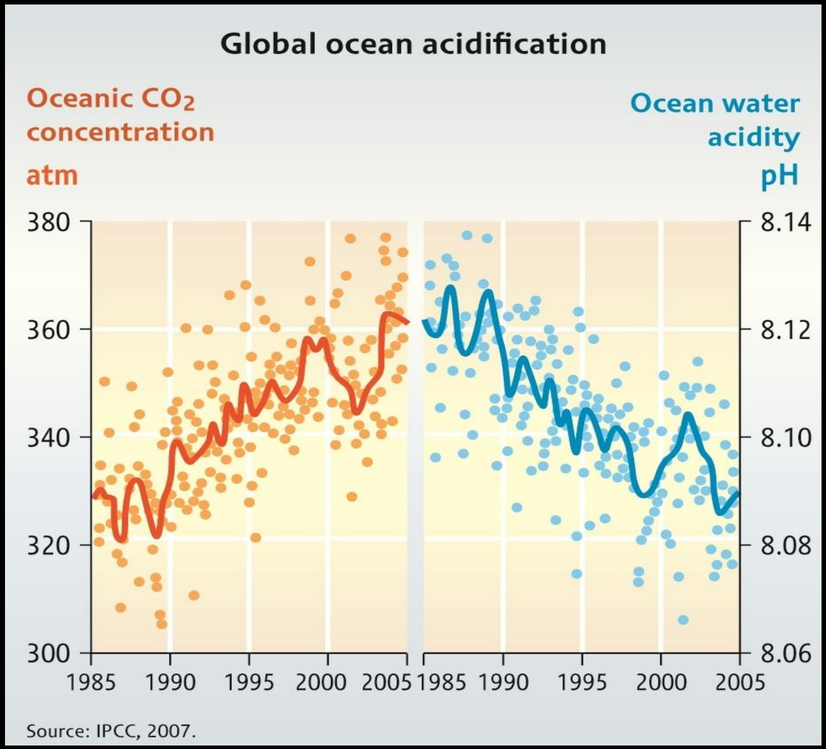
- also ocean surface whitening – floating white tiles

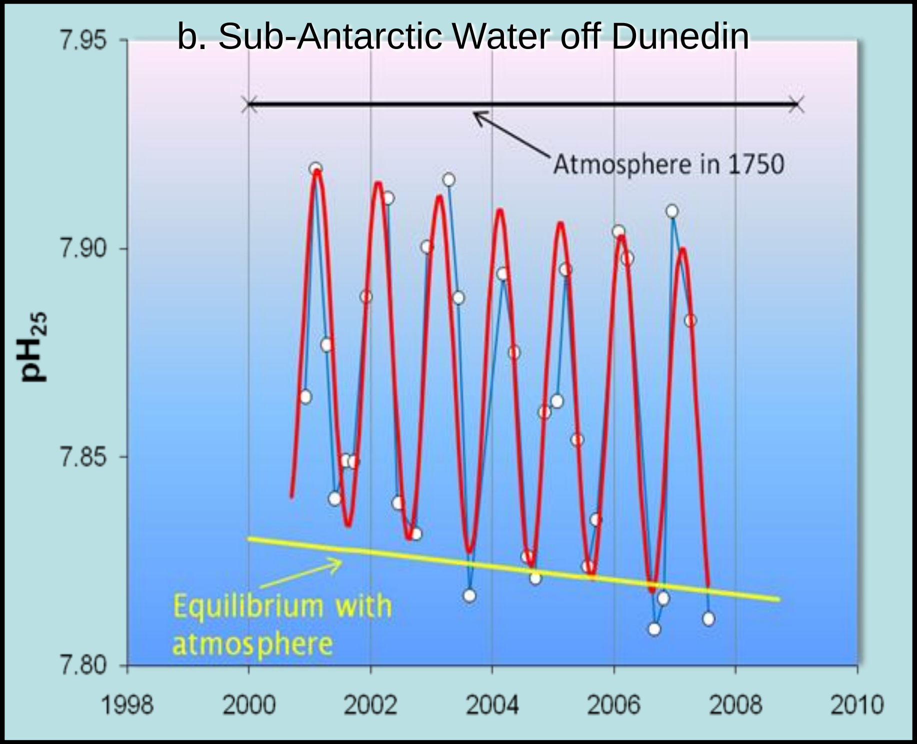
- Indirect effects on marine ecosystems (light availability, precipitation)

- does not solve ocean acidification

www.eartheasy.com

Acidification of the ocean by CO_2 uptake





Today the oceans are 30% more acidic than before the industrial revolution.

Slide courtesy Keith Hunter, Dept Chem., University Otago

Direct addition – sub-seabed CO_2 storage

Requirements

appropriate site selection based on geological information,
a monitoring programme to detect problems,
a regulatory system and
the use of remediation methods to stop or control CO_2 releases if they arise

Risks

CO_2 loss :-

a) while being transported,
b) abrupt leakage from storage via injection well failure, or leakage up an abandoned well; and
c) gradual leakage, through undetected faults, fractures, or wells.

local health,safety and environment risks would be comparable to risks of current activities such as natural gas storage and enhanced oil recovery.